

A SYSTEM AND METHOD FOR CONTINUOUS CASTING OF A MOLTEN MATERIAL

FIELD OF THE INVENTION

5 **[0001]** The present invention relates generally to a system and method for
controlling the solidification of a molten material and, more particularly, to a
system and method for continuous casting of a molten material into a flat product
in a single step. Flat product is variously referred to as thin flat product, sheet,
strip, ribbon or foil depending on thickness and width, and on the industrial
10 application.

BACKGROUND OF THE INVENTION

15 **[0002]** Continuous spin-casting is a process where molten metal is forced
through a nozzle onto a substrate where it freezes and is spun off as ribbon
product. The contacting interface between the substrate and the molten metal
affects the surfaces (top or bottom sides) of the resulting ribbon product. With
respect to thicker ribbon product, i.e. ribbon product having a thickness greater
than about 50 mm, the effects on the surface only impact a small fraction of the
thickness of the ribbon product and thus generally are negligible. However, as the
20 ribbon product becomes thinner, i.e. has a ribbon product thickness less than about
1 mm, the effects on the surface of the ribbon product impact a larger percentage
of the thickness of the ribbon product. As a result, substantially single step
continuous casting has only been used to a limited extent commercially to produce
flat product. One example of such a continuous spin-casting process that has been
25 used commercially is disclosed in U.S. Patent No. 4,142,571 to Narasimhan which
is herein incorporated by reference.

30 **[0003]** Instead one prior technique to produce a thin ribbon product, such
as aluminum sheet, is to first cast, on the order of about 500 mm thick, a thick slab
using the twin-roll process or otherwise and then to subject the slab to a sequence
of hot and cold rolling stages until the thickness of the slab is reduced on the order
of 10^4 : Although this process works, it requires a number of steps, a large
capital investment, generates considerable scrap and consumes a relatively large
amount of energy.

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SUMMARY OF THE INVENTION

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[0009] The present invention provides a process for high speed (throughput) casting of flat product of high quality. Gradient patterns are created by a substantially uniform source at microscale, laser hot spots or droplets that dry to make dots of thin solid film on the substrate. This uniform source is then
5 "printed" in a pattern to make a desired gradient on the macroscale. The effect is a continuum or gradient on the macroscale because of the difference in length scale between dots and patterns and because of the number of spots.

[0010] The present invention provides a system and method for
10 continuous casting of molten metals to the specifications of the designer and also for coating a product with a molten material. Reducing the number of processing steps by using the present invention will also greatly reduce the cost of the manufacturing equipment needed and, in some cases, will also yield significant increases in productivity when compared against prior manufacturing techniques.
15 Further, the present invention is 'tunable' to permit a manufacturer to manipulate the form of the final product providing manufacturers with greater flexibility in meeting specific demands. By simplifying the manufacturing process and reducing the amount of scrap, the present invention will also save energy when compared against prior manufacturing techniques and thereby will substantially
20 reduce CO₂ emissions to the atmosphere.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a side view of a system for casting a molten material in accordance with one embodiment of the present invention;

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[0012] FIG. 2 is a side view of a system for casting a molten material in accordance with another embodiment of the present invention;

[0013] FIG. 3 is an enlarged, cross-sectional view of a contact zone region
30 (which is not to scale) in the system shown in FIG. 1. *The dimensions given on FIG 3 are approximate.*

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[0014] FIG. 4A is a side view of an alternative embodiment of a writing system for the system in accordance with the present invention;

[0015] FIG. 4B is a side view of yet another alternative embodiment of a writing system for the system in accordance with the present invention;

5 [0016] FIG. 5A is a diagram of a thermal gradient pattern on the substrate at a laser frequency of about two kilohertz without a prism and cross-stream translation of about one cm/s;

10 [0017] FIG. 5B is a diagram of a thermal gradient pattern on the substrate at a laser frequency of about two kilohertz with a prism;

[0018] FIG. 5C is a diagram of a thermal gradient pattern on the substrate at a laser frequency of about ten kilohertz without a prism; and

15 [0019] FIG. 5D is a diagram of a thermal gradient pattern on the substrate at a laser frequency of about ten kilohertz with a prism.

DETAILED DESCRIPTION

20 [0020] A system 10(1) for casting a molten material in accordance with one embodiment of the present invention is illustrated in FIG. 1. The system 10(1) includes a substrate 12 on which a molten material is deposited, a driving system 14 that rotates the substrate 12, a thermal writing system 15(1), and a source 18 for the molten material 20. A method in accordance with one embodiment includes rotating the substrate 12, generating a thermal gradient
25 pattern on at least a portion of the substrate 12, and depositing the molten material on at least a portion of the substrate 12 with the thermal gradient pattern. The present invention provides a number of advantages including providing a system and method for continuous casting of a molten material 20, in a single step, to the specifications of the designer and also a system and method for coating a product
30 with the molten material 20.

[0021] Referring to FIG. 1, the substrate 12 comprises a single wheel, although other types of substrates can be used, such as a belt or a product that is to

be coated with the molten material 20. In this particular embodiment, the substrate 12 has a circumference of about three meters and a width of about 12.5 cm, although the particular dimensions of the substrate 12 can vary as needed for the particular application. Although not shown, the substrate 12 may also include
5 a cooling system to actively cool the substrate 12 during the casting process.

[0022] The driving system 14 is coupled to the substrate 12 to rotate the substrate 12. A variety of different mechanical systems, such as a shaft or rollers on which the substrate 12 is seated and which are rotated by motor, can be used to
10 rotate the substrate 12.

[0023] The writing system 15(1) is a thermal writing system comprising a laser 16 and a laser control system 17, although other types of writing systems with other components, such as multiple lasers, can be used. An output end of the
15 laser 16 is adjacent to and spaced from a portion of the substrate 12 before the contact region or zone 22. The laser 16 generates a laser light signal that induces hot spots on a portion of the substrate 12 directly by heating or bare spots indirectly by removing a previously deposited thin solid film on the surface of the substrate 12. The laser control system 17 includes a processor coupled to a
20 memory which stores programmed instructions to be executed by the processor to set the characteristics of the generated laser light signal or beam and the position and movement of the laser light signal with respect to the substrate 12 to generate a desired thermal gradient pattern, although laser control system 17 can comprise other components and can operate in other manners. Adjusting the configuration
25 and/or characteristics of the pattern affects the resulting product 36 being produced. In this particular embodiment, the laser control system 17 manipulates the laser light signal from the laser 16 to traverse slowly in a crosswise direction across the width of the substrate 12, although the laser 16 can be manipulated to move in other directions. *The frequency of the laser can also be manipulated while the laser moves.* *PP 2/16/02*
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[0024] As shown in an alternative embodiment in FIG. 4A, the thermal writing system may also include a focusing lens 24 and a prism 26. In this embodiment, the focusing lens 24 and the prism 26 reflect the laser light signal

generated by the laser 16 on to a portion of the substrate 12, although the prism 26 can be configured to reflect the light in other directions. As shown in yet another alternative embodiment, the thermal writing system may just include the focusing lens 24. In this embodiment, the focusing lens 24 directs the laser light signal
5 generated by the laser 16 on to a portion of the molten material 20 to condition the molten material before depositing it on the substrate 12, although the lens can be positioned to reflect the light in other directions.

[0025] Referring to FIGS. 1 and 3, the source 18 for the molten material
10 includes a container or crucible 30 for holding the molten material, a nozzle 32, and a pressure system 34, although the source 18 for molten material can be comprised of other types of and combinations of elements. The nozzle 32 of the source 18 is formed in the container 30 and is positioned adjacent to and spaced from the substrate 12, although other types of nozzles which are part of or are
15 connected to the container 30 can be used. In this particular embodiment, the pressure system 34 comprises a tank of pressurized inert gas, such as Argon, which is supplied to the container 30 via a tube or other conduit. The supplied gas applies pressure on to the molten material 20 to control the flow of the molten material 20 out of the container 30 on to the substrate 12. In this particular
20 embodiment, pressure system 34 is a gas pressure system, although other types of pressure systems, such as a mechanical system can be used depending on the particular application. In another embodiment, a tundish can feed the molten material 20 into the container 30 from where it would be forced onto the substrate 12.

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[0026] A system 10(2) for casting a molten material in accordance with another embodiment of the present invention is illustrated in FIG. 2. System 10(2) is identical to System 10(1) except as described below. Elements in FIG. 2 which are the same as those in FIG. 1 have numeral designations which
30 correspond to those in FIG. 1 and will not be described in detail here.

[0027] In system 10(2), the writing system 15(2) is a compositional writing system comprising a nozzle 21 and a compositional distribution

system 23, although other types of writing systems with other components, such as with multiple nozzles, can be used. An output end of the nozzle 21 is adjacent to and spaced from a portion of the substrate 12 before the contact region or zone 22. The compositional distribution system 23 includes a processor which
5 executes programmed instructions stored in a memory to set the characteristics of the distribution of material on to the substrate 12 to generate a desired compositional gradient pattern, although compositional distribution system 23 can comprise other components and can operate in other manners. A sensor 29 is coupled by a feedback loop to the compositional distribution system 23. The
10 sensor 29 provides information about the ^{effect of the} compositional gradient pattern ^{on} of the resulting product 36 which the processor in system 23 uses to adjust the distribution of material on ^{the} substrate 12 ^{by means of an appropriate control}. In this embodiment, the nozzle 21 is ^{algorithm.} under the control of the compositional distribution system 23 and distributes dots or other portions of material on a portion of the substrate 12, for example portions
15 of liquid that dry quickly to form solid film. Adjusting the configuration and/or characteristics of the pattern affects the resulting product 36 being produced. A variety of different materials can be deposited on the substrate 12. In this particular embodiment, the compositional distribution system 23 manipulates the
nozzle 21 to traverse slowly in a crosswise direction across the width of the
20 substrate 12 as material is being deposited, although the ^{write nozzle 21} laser 16 can be manipulated to move in other directions.

[0028] System 10(2) also includes an erasing system 28 that cleans or un-conditions the surface of the substrate 12. The type of erasing system 28 used
25 depends on the writing system 15 used. Since in this particular embodiment, the writing system 15(2) lays down a pattern of dots of solid film on the substrate 12, the erasing system 28 is an abrasion system, although other types of erasing systems could be used. The erasing system 28 includes an emory or other abrasive cloth or material on a counter-rotating drum that removes the portions of
30 film by being abrasive against the substrate 12, although erasing system 28 can comprise other types of components that operate in other manners. If, for example, the writing system removed thin solid film by laser ablation, then the erasing system 28 may comprise an abrasion system and a deposition system,

although erasing system 28 could comprise other components that operate in other manners. The abrasion system would treat, i.e. abrade, at least a portion of the surface of the substrate 12 and then the deposition system would lay down a new continuous thin solid film^{on} at least a portion of the surface of the substrate 12. If, in another example, the writing system is thermal writing system 15(1) as shown and describe herein with reference to FIG. 1, then an erasing system will generally not be needed since thermal conduction within the substrate 12 smoothes out the hot spots with time. For this to work, the substrate 12 is made of a material that is sufficiently conductive, such as Cu-Be, and there must be sufficient time (distance) between the nozzle 32 and the writing system 15(1) for the thermal gradient pattern to dissipate.

[0029] Accordingly, the writing system 15 is any mechanism by which the elements of a pattern can be imposed on the surface of the substrate 12 – hot spots, materials spots or the absence of material spots are all examples – and which can be sufficiently controlled to form patterns that “appear” continuous on the scale of features relating to the quality of the product or form patterns on the molten material 20 as it is being deposited. The writing system 15 conditions the substrate 12 or molten material 20 with a pattern. The erasing system 28 is any mechanism by which the action of the write system 28 is eliminated, removed, or unconditioned.

[0030] A method for continuous casting of a molten material in accordance with one embodiment will now be described with reference to FIG. 1. The driving system 14 is engaged to begin to rotate the substrate 12. In this particular embodiment, the substrate 12 is rotated at a casting speed on the order of about ten m/s (linear velocity) to achieves solidification rates of the molten material on the order of about ten cm/s for aluminum, although the particular speed of rotation of the substrate 12 can vary as needed for the particular application.

[0031] Once the desired rotational speed for the substrate 12 is reached, the laser control system 17 controls the laser light signal or beam from the laser 16

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to generate a thermal gradient pattern on a portion of the surface of the substrate 12. The goal is to generate a temperature disturbance which is enough to influence the solidification. In this particular example, the laser 16 outputs a laser

light signal of wavelength about 1064 nm, although the characteristics of the light signal can vary based on the particular application. The laser light signal induces a temperature disturbance whose amplitude depends on the volume of the

substrate 12 heated. The volume heated is determined by the footprint of the spot and the depth of heating given by the thermal diffusion length. The heated depth can be taken to be constant because the pulse duration of the laser light signal is nearly constant with laser frequency for this embodiment. For example, for a duration of about 100ns for the laser light signal, the depth is a few μm .

Primarily, for a given substrate the footprint is determined by the optics built into the laser and the optics in the light path from the laser to its impingement on the substrate, in the embodiment in FIG. 4A this is the focusing lens 24 and the

prism 26. The nature of the substrates and wavelength of light together determine how much light energy the substrate absorbs and how much it reflects. The temperature rise is inversely proportional to the square of the footprint length making it very sensitive to the optics used, i.e. the focusing lens and prism. For example, if 0.1 mJ of the energy is absorbed from a laser light signal or pulse, a footprint scale of 100 micron gives about a 10^3 K temperature rise (near ablation) for a Cu-Be substrate while a one mm scale gives about a 10 K rise.

[0032] The thermal gradient pattern formed by the laser light signal is imposed on the substrate 12 before the contact region or zone 22 where the molten material 20 is deposited on the substrate 12. In this particular embodiment, the thermal gradient pattern has a plurality of thermal spots generated by the laser light signal heating the surface of the substrate 12 where the size of each spot is about ten microns and the spacing between spots is about 100 microns. Although one type of pattern is disclosed here, the type of thermal gradient pattern generated by the laser light signal will vary based upon the particular requirements of the product being produced. Some examples of other thermal gradient patterns which could be imposed on the substrate 12 are illustrated in FIGS. 5A-5D.

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A laser-like device with signal in the visible, ultraviolet, infrared or any other part of the spectrum of electromagnetic radiation can be used depending on the application.

[0033] When generating a thermal gradient pattern, the rate of decay of the spots should be considered. Spots in the thermal gradient pattern generated by the laser light signal decay and spread on a thermal diffusion time. Heat will diffuse 100 microns in a substrate 12 made of copper-beryllium (Cu-Be) in about 100 μ s during which time the substrate moves one mm (10 m/s motion and thermal diffusivity of order $10^{-4} \text{ m}^2/\text{s}$). As a result, in this particular embodiment spots in the thermal gradient pattern are created close to the nozzle 32, within one cm or closer in the embodiment shown in FIG. 4, to maintain spatial resolution until the contact zone 22. Additionally, in this particular embodiment in order to obtain spatial resolution of order 100 microns with a substrate 12 rotating at a speed of ten m/s, the laser 16 needs to be operated at a pulse rate of 100 kHz.

[0034] To generate two dimensional thermal gradient patterns, a technique to rapidly raster the laser light signal in a cross-stream direction is required. By way of example only, acousto-optical (AO) deflection of the laser light signal is possible using Bragg-cell technology at rates up to 100 kHz, although other techniques for creating two dimensional patterns could be used. In this particular example, AO scanners are utilized to deflect the incident laser light signal and control its location in the cross-stream direction. With a Bragg-cell driven by a frequency synthesizer and an amplifier, the incident laser light signal can be modulated at frequencies as high as 100 kHz. The Bragg-cell itself will be driven at much higher frequencies (80 MHz) and can produce deflection angles of order one degree with an accuracy of well within one in one hundred. By placing the Bragg-cell only a few centimeters from the substrate 12, the spatial location of the laser light signal on the substrate 12 can be controlled to the required accuracy.

[0035] Although in this particular embodiment, a thermal gradient pattern is generated on the substrate 12 to influence the solidification event, other types of patterns can be imposed on substrate 12. For example, a thin insulating film could be deposited on the substrate 12 and the laser light signal could be used to expose a compositional pattern in the film on the substrate 12 before the molten material is deposited. This is an example of negative templating. Patterns on the substrate 12 can also be imposed by chemical conditioning.

[0036] In another example, the embodiment shown in FIG. 2 operates the same as the one shown in FIG. 1 except for the operation of the writing system 15(2) and the erasing system 28. In this embodiment, the nozzle 21 deposits a pattern of dots or other portions of material on to at least a portion of the surface of the substrate 12 to form the gradient pattern. The conditioning of the substrate 12 with a gradient pattern, thermally or compositionally, can be applied and removed in substantially real time.

10 [0037] Referring back to the discussion of the operation of the system 10(1) shown in FIG. 1, in this particular embodiment as shown in FIG. 3 (which is not to scale), the pressure system 34 applies a gas pressure to the molten material 20 in the container 30 which causes the molten material 20 to be forced out through the nozzle 32. In this particular embodiment, micro-positioners on the
15 overhead carriage (not shown) allow the nozzle 32 to be positioned precisely above the apex of the substrate 12, although the nozzle 32 can be oriented in different ways and at different locations depending on the application. In this particular embodiment, the dispensing end of the nozzle 32 is positioned so close to the substrate 12 that the nozzle interferes with the flow, although the particular
20 position of the nozzle 32 can vary as needed for the particular application. Additionally, in this particular embodiment the molten material 20 is deposited at a rate of ~~at the rate of~~ $10 \text{ cm}^2/\text{s}$ per unit width on to the substrate 12, although the particular rate can vary as needed for the particular application. The nozzle 32 dispenses the molten material 20 on to a portion of the substrate 12 to form a
25 puddle of molten material 20 which solidifies or freezes to form the product 36. Typically, the puddle length L is one hundred times the ribbon thickness T and twenty times the gap G , although these dimension can vary as needed. ~~This~~ ~~disparity of length scales motivates the 'long puddle' limit, $L/G \gg 1$.~~ In addition to the overpressure ΔP and the substrate velocity U , parameters which effect the
30 dimensions of the resulting product 36 include the dimensions of gap G and of slot breadth B . Solidification takes place on contact with the substrate at a rate V that varies along the front. A ribbon of thickness T is spun or carried off from the substrate at a velocity U . The appropriate Reynolds number is based on mass

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throughput: $Re = \bar{u}G/v \sim 2 * 10^3$ where $\bar{u} \equiv (T/G)U$. The stabilizing influence of suction (due to solidification) maintains a substantially laminar flow in the gap. By way of example only, if the molten material 20 is aluminum, it has a melting temperature of about $\theta_m = 660^\circ C$. The principal thermal control parameters are

5 the temperature of the nozzle 32 which in this particular example is ($\theta_h \sim 720^\circ C$), the temperature of the substrate 12 which in this particular example is ($\theta_c \sim 30^\circ C$), and the contact heat-transfer coefficient H which in this particular example is about ($\sim 10^5 W/cm^2 K$).

10 **[0038]** When the molten material 20 is dispensed on to the portion of the substrate 12 with the pattern, in this particular example a thermal gradient pattern, the pattern ^a affects the solidification of the molten material 20 and thus the resulting end product 36. The pattern imposed on the substrate 12 permits a high quality ribbon product having a thickness less than about 1 mm to be produced at

15 high rates.

[0039] In the operation of the embodiment shown in FIG. 1, an erasing system 28 is not needed because the thermal gradient pattern will dissipate before the next thermal gradient pattern is written on the surface of the substrate 12 as

20 discussed earlier herein. In an another example for the operation of FIG. 1 where the writing system 15(1) uses the laser 16 for ablation, an erasing system may be used to remove any remaining pattern and to add a thin film of material onto the surface of the substrate 12. The erasing system removes the prior gradient pattern and prepares the surface for subsequent ablation. By way of example only, such

25 an erasing system may spray a film, such as BN, on the substrate 12 to erase a prior pattern. The laser 16 will then write a new pattern on to a portion of the film on the substrate 12.

[0040] In the operation of the system 10(2) shown in FIG. 2, an erasing

30 system 28 is positioned after the contact zone 22 to remove the compositional gradient pattern formed on the surface of substrate 12. The erasing system 28 brings the substrate 12 back to an unconditioned state by removing the pattern,

such as by abrading the pattern from the surface of the substrate as described earlier. The surface of the substrate 12 is then ready for the application of the next compositional gradient pattern.

5 **[0041]** Accordingly, the present invention provides a system and method
for continuous casting of molten metals, in substantially a single step, to the
specifications of the designer and also for coating a product with a molten
material. The system and method reduce the number of processing steps required
to produce a thin ribbon product from a molten material and the number of steps
10 needed to coat a product with a molten material. Reducing the number of
processing steps provides a number of benefits, including reducing capital costs,
manufacturing costs, and saving energy.

15 **[0042]** Having thus described the basic concept of the invention, it will be
rather apparent to those skilled in the art that the foregoing detailed disclosure is
intended to be presented by way of example only, and is not limiting. Various
alterations, improvements, and modifications will occur and are intended to those
skilled in the art, though not expressly stated herein. These alterations,
improvements, and modifications are intended to be suggested hereby, and are
20 within the spirit and scope of the invention. Accordingly, the invention is limited
only by the following claims and equivalents thereto.